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Stratospheric Transparency Derived from Total Lunar Eclipse Colors, 1801–1881

RICHARD B. STOTHERS

NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025; rstothers@giss.nasa.gov

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ABSTRACT. Contemporary journals have been searched for published accounts of the observed colors of total lunar eclipses in the period 1801–1881. The result is a catalog of 31 reported lunar eclipses. A dark eclipse on a clear night usually implies the presence of significant turbidity in the Earth's stratosphere arising from a recent volcanic eruption. The totally eclipsed Moon became invisible (or nearly so) in the year after the great 1815 eruption of Tambora. Eclipse data compiled here cast doubt on any significant penetration of the stratosphere for a number of other large volcanic eruptions, but are too sparsely distributed in time to say anything conclusive about certain others.

1. INTRODUCTION

The red face of the totally eclipsed Moon assumes its color from the faint illumination by Sun rays refracted and scattered into the shadow cone by the Earth's upper atmosphere. A catalog of reported total lunar eclipse colors dating from the beginning of modern scientific periodicals in 1665 up to 1800 has recently been published (Stothers 2004), and a sequel for the years 1801–1881 is presented here. The new catalog ends with the inception of accurate pyrheliometric observations of the upper atmosphere in 1881. The great eruption of the volcano Krakatau occurred 2 years later, pumping a prodigious amount of dust and gas into the upper atmosphere and leading to a series of very dark lunar eclipses in the following 2 years (Flammarion 1884; Link 1961; Keen 2001). It is thus as a measure of stratospheric turbidity that lunar eclipse colors are now regarded as having the most scientific value.

2. DATA AND METHODS

Lunar eclipse reports during the 19th century crop up in all kinds of published journals: scientific, general, and even popular. Almost 300 journals, together with a few scientific monographs, were systematically examined for the present survey. However, no newspapers, newsletters, pamphlets, diaries, ships' logs, or other kinds of informal materials were consulted. Inevitably, a number of lunar eclipse reports must therefore have been missed. On the other hand, the vast majority of usable reports come from the scientific journals, and after about 1820, from the astronomical journals in particular. Until 1860, only about half of all total lunar eclipses were reported; thereafter, almost all of them were.

Previous searches of the literature from the 19th century either have not resulted in any actual publication of the lunar eclipse data and sources that were discovered (Houzeau & Lancaster 1887; Danjon 1920a), or have not ranged widely enough (Fisher 1924). Fisher's study encompassed only about two dozen journals dealing with our period, and it only covered eclipses between 1860 and 1922. Unfortunately, his study focused exclusively on the visibility of lunar spots as seen through instruments of prescribed power. This "telescopic" method of estimating lunar eclipse brightness gave ambiguous results, however, since different observers came up with widely differing spot visibilities, and this method was never used again.

A more useful approach was adopted by Keen (1983, 2001) for lunar eclipses occurring in the two periods 1880–1888 and 1960–2001. It employs naked-eye observations of the average color of the totally eclipsed disk, with occasional supplemental observations of the brightness and color of the Moon's rim. The method was originally developed by Danjon (1920a, 1920b), who defined a rough scale of luminosity L:

$L = 0$: Very dark eclipse. Moon almost invisible.

$L = 1$: Dark eclipse, gray or brownish. Details difficult to make out.

$L = 2$: Deep red or russet eclipse. Very dark at the center of the shadow. Rather bright rim.

$L = 3$: Brick red eclipse. Shadow often with a rather bright gray or yellow rim.

$L = 4$: Very bright copper red or orange eclipse. Very luminous, bluish rim.

Maunder (1921) showed persuasively that only total lunar eclipses, and not partial ones, should be used for accurate results with this method. Keen's (1983) data for 1960–1982 suggest average values of the corresponding excess atmospheric visual optical depths of $\tau_{\rm vis} = 0.10$ (or greater), 0.04, 0.02, 0.01, and 0.00 for $L = 0$, 1, 2, 3, and 4, respectively. We adopt this method here, as we did before.

3. CATALOG

Data on the visibility and color of the totally eclipsed Moon in a clear sky are summarized in Table 1, where the color data for the disk itself are quoted in the reports' original language. Estimates of L have been made from these collected data; a default value of $L = 4$ is used if the data lack sufficient detail. The dates listed are taken from von Oppolzer's (1887) catalog of predicted lunar eclipses, which also provides the expected magnitudes, times, and other relevant information. For the whole period 1801–1881, von Oppolzer lists 54 total lunar eclipses, of which we have found observational data for 31.

As was the case in the 18th century, most of the 19th century reports come from Europe. Other geographical areas include the United States (Rutherfurd 1848; Peters 1867; Hall 1881; Hooper 1881; Taylor 1883), Mexico (Poey 1866a, 1866b), Chile (Moesta 1857; Volckmann 1857), Tibet (Moorcroft 1817), India (Anonymous 1823; de Schlagintweit 1861; Anonymous 1873), and Australia (Rümker 1829a, 1829b; Tebbutt 1866, 1867, 1870a, 1870b, 1870c, 1873, 1880a, 1880b; Russell 1880; Anonymous 1880).

Eclipses noted with asterisks in Table 1 present some puzzling or interesting aspects that are discussed below. We need not comment here on the reports of red points of light seen on the eclipsed disk, because these refer to telescopic observations of the lunar highlands, as first noted by Herschel (1792).

1805 July 11

Although Chiminello (1805) described the Moon in this eclipse as being invisible or difficult to see, purportedly as in the eclipse of 1783 September 10, Cerquero (1831) called its color "bright copper." All contemporary observers of the 1783 eclipse reported a normal color, albeit somewhat dark (Stothers 2004), and so we may ignore Chiminello's rather exaggerated characterization of both eclipses.

1816 June 10

This celebrated eclipse was one of the darkest ever reported, the Moon appearing to vanish in a clear sky, according to Lofft (1816), Lee (1819), and Beaufoy (1826) in England and Eule (Bode 1820b) and Bode (1820a) in Germany (Table 1). Eule, however, noticed that the Moon would sometimes reappear temporarily, while it was also faintly seen in Bohemia by David et al. (1820), and probably in Austria by Triesnecker & Bürg (1820), who were able to make out its position on the sky. Some caution is necessary here, because in Central Europe the Moon was lying low near the horizon, with dawn coming on (Bode 1820a). On the other hand, the eclipse in England occurred around 1:30 in the morning (Lofft 1816), which confirms that this was a genuinely dark eclipse (Beer & Mädler 1837; Flammarion 1884; Link 1961, 1963). The cause of the darkening was almost certainly the enormous eruption of the volcano Tambora in Indonesia in 1815 April (Dufour 1899). Optical phenomena in the atmosphere during the years 1815–1817, such as colored twilight glows, naked-eye visibility of sunspots, and high stellar extinction, suggest that $\tau_{vis} \approx 1$, a value that is certainly consistent with independent estimates of volcanic aerosol production based on Greenland ice-core acidities (Stothers 1984, 1996). On the other hand, petrological analysis of the locally erupted Tambora magma—an indirect and generally less certain method—favors a value only half as large as this (Self et al. 2004). In either case, the optical depth must have been considerably larger than the minimum of 0.1 based on the eclipse darkness. An atmospheric feature that seemed to be missing in the contemporary accounts was the presence of a large reddish halo (Bishop's ring) around the Sun; Weber (1815), however, did report one from Germany on June 16, with a radius of about $22\overset{\circ}{.}5$. This estimate agrees well with ring sizes measured after other large volcanic eruptions (Stothers 1996).

1826 May 21 and November 14

Rümker's (1829a, 1829b) statement that the darkness of these two lunar eclipses was sufficient to facilitate the telescopic observation of very faint stars certainly does not imply, for either case, a truly dark eclipse. A similar exaggerated characterization of "total darkness" during the eclipse of 1833 December 26 (Anonymous 1834) is clearly contradicted by the author's provision of the measured time of the greatest obscuration.

1856 October 13

Although totality was predicted to last 7 minutes (von Oppolzer 1887), all explicit reports from contemporary observers refer to the Moon as being only partially eclipsed (Bulard 1856; Faye 1856; Rümker 1856; Schmidt 1856). Since European observers would have been the best placed, the three reports from Chile (Moesta 1857; Volckmann 1857) and India (de Schlagintweit 1861) can be ignored in favor of the other reports.

1863 June 1

Jenkins (1880) claimed that the Moon was invisible from England, as it was during the eclipse of 1816 June 10. He was immediately contradicted by Backhouse (1880), who pointed out that the Moon, while dark, was not invisible, and that the darkness of this midnight eclipse might have been due to a local fogginess in the air. Many other observers (Table 1) mention a dark red color of the Moon.

1881 December 5

According to von Oppolzer (1887), totality was expected to last less than 1 minute. However, this eclipse is included here, and Keen (2001) also has used it.

4. CONCLUSION

When volcanic eruptions emplace a large amount of sulfate aerosol in the stratosphere, lunar eclipses can become noticeably darker than normal. We have already remarked that in the

TABLE 1
CATALOG OF TOTAL LUNAR ECLIPSE COLORS, 1801–1881

Date	*L*	Description of Disk	References
*1805 July 11	4	Almost invisible	Chiminello 1805
		Bright copper (hellen Kupferfarbe)	Cerquero 1831
1812 Feb 27	4	Visible	Lofft 1812
1812 Aug 22	4	Visible	Moorcroft 1817
*1816 Jun 10	0	Invisible	Lofft 1816; Lee 1819; Bode 1820a; Eule in Bode 1820b; Beaufoy 1826
		Faint	Triesnecker & Bürg 1820; David et al. 1820
1823 Jan 26	4	Visible	Anonymous 1823; Rümker 1829a
		Milky (milchigten)	Pastorff 1827
		Coppery red (kupferrother)	Bode 1827
1823 Jul 23	3	Very red (sehr rother)	Gambart 1828
*1826 May 21	2	Darker than usual	Rümker 1829a, 1829b
*1826 Nov 14	2	Darker than usual	Rümker 1829b
1830 Sep 2	3	Coppery or blood red	Anonymous 1830
		Strong red (starkes röthliches)	David 1831
1833 Dec 26	3	Red	Robinson 1834
		Dark red (dunkler röthlichen)	Pastorff 1834
		Very vivid red (Röthe sehr lebhaft)	Beer & Mädler 1837
		Glowing red (glühendrothen)	Schwabe 1833
		Swarthy copper with bluish green limb	Herschel 1835
1837 Oct 13	3	Reddish (rougeâtre)	Quetelet 1857
		Dull reddish	Anonymous 1837
		Red patches	J. Herschel in Brown 1866
1841 Feb 6	3	Red (roth)	Mädler 1842
		Reddish (röthliche)	Encke 1844
		Reddish (rougeâtre)	Quetelet 1857
		Bright, very rosy (heller, fast rosenroth)	Argelander 1841
1844 May 31	3	Red (rossa)	De Vico 1844
		Red (rothe)	Anger 1844
		Reddish (rougeâtre)	Arago 1844
		Reddish (röthlich) with ashen limb	Encke 1848
		Coppery	Anonymous 1844
		Dark copper-red (dunklem Kupferroth) with light blue limb	Gauss 1844
1844 Nov 24	3	Red (rosso)	De Vico 1845
		Deep red (tiefrothen)	Mädler 1845a, 1845b; Rümker 1845
1848 Mar 19	3	Strong red (Roth stark)	Schmidt 1849
		Dirty fiery red (schmutzig feuerroth)	Petersen 1848
		Deep red, bright	Forster 1848a, 1848b; Walkey 1848a, 1848b
		Dullish red, tarnished copper	Mayne 1848a, 1848b
		Dark red (rouge obscur)	Babinet 1848
1848 Sep 13	3	Deep red copper with greyish green limb	Rutherfurd 1848
1852 Jan 7	3	Very intense red (rothe sehr intensiv)	Wolf 1852
		Dark red (dunkelroth)	d'Arrest 1852
1855 May 2	4	Coppery red (kupferrothe)	Quetelet in Anonymous 1855
*1856 Oct 13	4	Coppery red (rouge cuivrée)	Bulard 1856; Moigno 1856
		Dark yellow (dunkelgelbem) to blackish red (schwärzlich rothe)	Rümker 1856
*1863 Jun 1	3	Dark but not invisible	Backhouse 1880
		Visible	Bianchi 1863
		Red (röthlicher)	Theil 1863
		Brilliant red (rouge éclatant)	Tempel 1863
		Very intensely reddish (rougeâtre très-intense)	Flammarion 1863, 1907
		Dusky red	Anonymous 1863a
		Coppery red (rouge cuivrée)	Birt 1863; Anonymous 1863b, 1863c
		Dark coppery (sombre cuivrée), bloody peaks	Figuier 1864
1866 Mar 31	4	Bright cherry brown (hell kirschbraunen)	Peters 1867
		Reddish to rose (rougeâtre tirant au rose)	Poey 1866a, 1866b
		Dull red	Brown 1866
1866 Sep 24	4	Bright copper	Tebbutt 1866, 1867
1870 Jan 17	4	Copper	Tebbutt 1870a, 1870b, 1870c

TABLE 1 (*Continued*)

Date	*L*	Description of Disk	References
1870 Jul 12	4	Visible	Flammarion 1907
		Reddish	Weston 1870; Thompson 1870
		Reddish brown (röthlich braunem)	Falb 1870
		Dull ruddy orange	Buffham 1870
		Copper	Jackson 1870; Anonymous 1870; Browning 1871
		Copper with green limb	Walker 1870
1873 May 12	3	Dull red with straw limb	Tebbutt 1873
1873 Nov 4	2	Darker than usual	Anonymous 1873
1877 Feb 27	4	Bluish	Penrose 1877
		Red	Arcimis 1877; de Konkoly 1878
		Vividly red	Noble 1877
		Intensely red (rossa intensa)	Riccò 1889
		Reddish tending to pink (rougeâtre tendant vers le rose)	Perrotin 1877, 1880
		Dark red (dunkel roth) to dark red-yellow dunkel roth-gelb)	von Sternach 1877
		Dusky red to pale golden with sea-green limb	Freeman 1877
		Red-brown (rothbraun) with blue-green limb	Bruhns 1878
		Cloudy dull brick-red	Perry 1877
		Red copper, smoky orange red	Todd 1878
		Coppery red	Barber 1877
		Weak, copper	Capron 1877a, 1877b; Anonymous 1877a
		Reddish points of light	Dorna 1877
1877 Aug 23	4	Red	Noble 1877; Ashley 1877
		Reddish	Detaille 1877; Flammarion 1907
		Reddish yellow	Anonymous 1877b
		Dull red	Brown 1877; Plummer 1877
		Orange, reddened	Johnson 1877
		Smoky brown-red (rauchiges braunroth)	Klinkerfues 1877
		Copper	Christie & Maunder in Airy 1877; Anonymous 1877c
		Copper red (kupferroth)	Leppig 1878
		Dark copper	Elger 1877; Dennett 1877
		Ruddy copper with golden limb, red spots	Capron 1877c
1880 Jun 22	4	Visible	Tebbutt 1880a
		Red	Russell 1880
		Copper-red	Anonymous 1880
1880 Dec 16	3	Dull red with straw limb	Tebbutt 1880b
1881 Jun 12	4	Bright	Taylor 1883
		Dull orange red	Hooper 1881
		Dull copper	Hall 1881
*1881 Dec 5	3	Red	Johnson 1881; Capron 1882a, 1882b

19th century the eruptions of Tambora (1815) and Krakatau (1883) produced extreme eclipse darkening. Is there any evidence of stratospheric turbidity due to lesser eruptions of that time?

According to Newhall & Self (1982), the largest known volcanic eruptions in the period 1801–1881 were those of Tambora (1815), Sheveluch (1854), and Askja (1875); the eruption of Cosiguina in Mexico (1835) is no longer considered to have been a large one (Self & Rampino 1988; Self et al. 1989). Lunar eclipse data confirm the great magnitude of Tambora. However, the volcanoes Sheveluch in Kamchatka and Askja in Iceland lie at such high latitudes that they would not be expected to have delivered a stratospheric aerosol cloud farther south than about 30°N (Stothers 1996). This would have left about 60% of the atmosphere unshrouded. The total eclipse of 1855 May 2 in fact displayed a normal color. Several other volcanic eruptions in the period 1855–1861 were once believed to have been large ones (Russell 1888; Sapper 1927; Lamb 1970) and therefore were accorded a sizable stratospheric impact (Mitchell 1970; Sato et al. 1993). However, the estimated magnitudes of those eruptions have been significantly downgraded by Newhall & Self (1982), and the purportedly largest one, Cotopaxi in Ecuador (1855–1856), was actually followed by a very bright total lunar eclipse on 1856 October 13.

Acidity measurements in Greenland ice cores provide independent evidence of large sulfur-rich volcanic eruptions. Clausen et al. (1997) have pointed out that a prominent acid signal occurs in all Greenland ice cores in the year 1816, undoubtedly due to Tambora's eruption the previous year. The only other signal for our period that they regard as volcanologically significant occurs in 1810, arising from an unknown large eruption at that time. If real, the eruption's atmospheric effects must

have dissipated by 1812 February 27 and August 22, when the totally eclipsed Moon was easily visible; however, highly colored twilights did appear in the second half of 1811 (Russell 1888). Greenland ice-core data derived by Zielinski et al. (1994) and Zielinski (1995) reveal two other large, closely spaced acid signals at about 1830–1831, perhaps due to Kliuchevskoi, Kamchatka (1829) and Babuyan, Philippines (1831). Unusual atmospheric effects were reported in the second half of 1831 (Russell 1888), but the next total lunar eclipse, in 1833 December 26, was normal in appearance. Antarctic ice cores display acid signals in 1809, 1816, 1831, and 1836 (Delmas et al. 1992; Cole-Dai et al. 2000), confirming that the first three were due to tropical eruptions, and leaving open the possibility that the 1836 signal came from a far Southern eruption.

It is possible now to conclude that total lunar eclipses serve as very sensitive detectors of large volcanic eruptions, subject to the important limitation of a rather crude temporal resolution. Total eclipses tend to occur in close pairs (separated by about half a year), so that the long-term average separation of 1.5 yr disguises the fact that successive separations are often more like 3 or 4 yr (see the data in von Oppolzer 1887). Nevertheless, we do possess a more-or-less complete record of reported total lunar eclipse colors from 1665 to 1881. The continuation of this record beyond 1881 (de Vaucouleurs 1944; Vassy 1956; Keen 1983, 2001), while it has some use, is at present largely superseded by other, more accurate methods of deriving stratospheric transparency.

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